Searches for the Most Metal-Poor Candidates from SDSS and SEGUE

Timothy C. Beers* and Daniela Carollo†

*Department of Physics & Astronomy, CSCE: Center for Study of Cosmic Evolution, and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, E. Lansing, MI 48824-1116, USA
†Osservatorio Astronomico di Torino, Italy, and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, E. Lansing, MI 48824-1116, USA

Abstract.
We report on efforts to identify large samples of very and extremely metal-poor stars based on medium-resolution spectroscopy and *ugriz* photometry obtained during the course of the Sloan Digital Sky Survey (SDSS), and its extension, SDSS-II, which includes the program SEGUE: Sloan Extension for Galactic Understanding and Exploration. To date, over 8000 stars with [Fe/H] ≤ -2.0 and effective temperatures in the range 4500 K $< T_{\rm eff} <$ 7000 K have been found, with the expected numbers in this temperature range to be well over 10,000 once SEGUE is completed. The numbers roughly double when one includes warmer blue stragglers and Blue Horizontal-Branch (BHB) stars in these counts. We show the observed low-metallicity tails of the Metallicity Distribution Functions for the cooler SDSS/SEGUE stars obtained thus far. We also comment on the confirmation of an inner/outer halo dichotomy in the Milky Way, and on how this realization may be used to direct searches for even more metal-poor stars in the near future.

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INTRODUCTION

The primary recent searches for metal-poor stars in the Galaxy (the HK survey of Beers and colleagues [1], and the Hamburg/ESO Survey of Christlieb and colleagues [2]) were based on objective-prism techniques, followed by many years of follow-up medium-resolution spectroscopy with intermediate-aperture telescopes. Although this approach has been spectacularly successful, and has resulted in the identification of several thousand stars with [Fe/H] < -2.0 (VMP stars according to [3]), and several hundred stars with [Fe/H] < -3.0 (EMP stars according to [3]), only three stars have been found to date with [Fe/H] < -4.0 (UMP according to [3]), several of which are discussed in detail by other contributions in this volume.

Clearly, much has already been learned from high-resolution spectroscopic studies of many of the HK and HES stars, but many questions concerning the nature of the first generations of objects born in the Galaxy remain – questions that can only be answered by obtaining a significant increase in the numbers of VMP, EMP, and especially UMP and HMP ([Fe/H] < -5.0 according to [3]) stars. New methods and new strategies are required. Here we report on one such effort, based on observations obtained during the SDSS and SEGUE [4]. Other survey methods and approaches are discussed by Christlieb et al. in this volume.

Kinematic studies of the SDSS stellar calibration objects, by Carollo et al. [5], has confirmed the (long suspected) dichotomy of the halo of the Milky Way. Aside from the obvious importance of this result for understanding the assembly and evolution history of the halo itself, the fact that the outer-halo population appears to exhibit a Metallicity Distribution Function (MDF) that peaks around [Fe/H] $= -2.2$, roughly 0.5 dex lower than that of the inner-halo population, opens up the possibility of specifically targeting the lowest metallicity stars in the Galaxy *if one could efficiently pre-select* likely members of the outer halo, as is discussed in more detail below.

METAL-POOR STARS DISCOVERED BY THE SDSS AND SEGUE SURVEYS

Metal-poor stars are identified from several sources within the SDSS and SEGUE. In the original SDSS, numerous metal-poor stars are found among the 16 (color- and apparent-magnitude selected) spectrophotometric and telluric calibration stars that are targeted each time an exposure of a spectroscopic plug-plate (containing a total of 640 fibers) is obtained. In addition, QSO candidates that turn out not to be quasars, and BHB candidates that turn out to be somewhat cooler than expected, based on spectroscopic follow-up, are often low-metallicity stars. Additional metal-poor stars are found among the calibration objects being observed during

the ongoing LEGACY spectroscopy program. The continuing SEGUE program specifically targets metal-poor stars, among the 13 or so categories it considers. There are also many metal-poor stars that are found among the F turnoff, G dwarf, and K giant target categories. As in SDSS, each SEGUE plug-plate obtains 16 calibration stars as well. The total number of stars observed spectroscopically by either SDSS or SEGUE is currently over 350,000. It should be noted that the color selection, either for the calibration objects or the low-metallicity candidates, is not capable of discriminating between stars of metallicity lower than [Fe/H] = -2.0, since the effect of declining metallicity on broadband stellar colors is minimal in this regime. Hence, the MDF of such stars should be relatively unbiased below this metallicity.

Stellar atmospheric parameters ($T_{\rm eff}$, log g, and [Fe/H]) are determined for SDSS/SEGUE stars by application of the SEGUE Stellar Parameter Pipeline (SSPP), which is described in detail by Lee at al. [6,7]. Tests of the SSPP indicate that, over the temperature range $4500 \leq T_{\rm eff} \leq 7500$ K, external accuracies in the derived parameters are on the order 120 K, 0.25 dex, and 0.2 dex, for $T_{\rm eff}$, log g, and [Fe/H], respectively.

Figure 1 shows the MDF for the over 4200 stars from SDSS with adopted [Fe/H] ≤ -2.0 (and with $S/N \geq 10/1$). Figure 2 shows the same distribution for the over 2400 similar stars observed during the first year of SEGUE. The addition of observations from LEGACY and from the second year of SEGUE increases the total numbers of stars with [Fe/H] ≤ -2.0 to well over 8000 objects in the temperature range considered herein. This already represents roughly a tripling of the total numbers of VMP stars obtained by the sum of all previous surveys conducted in the past half century since the low-metallicity star phenomenon was recognized.

It is clear from the shapes of the MDFs in Figures 1 and 2 that the total number of EMP stars (with [Fe/H] ≤ -3.0) is declining very rapidly, with only a handful of stars being identified to date with [Fe/H] ~ -4.0, and none below this value. We address the reasons for this below.

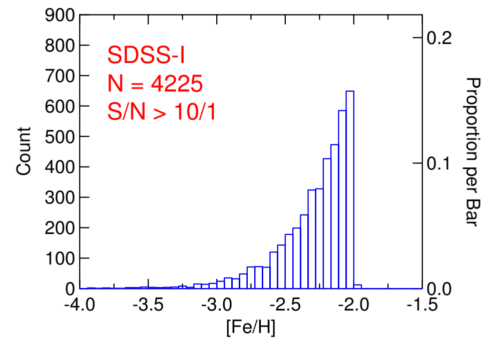

FIGURE 1. The MDF for VMP stars with 4500 K $< T_{\rm eff} <$ 7000 K observed during the course of SDSS-I. The great majority of these stars are objects taken for spectrophotometric and telluric calibrations.

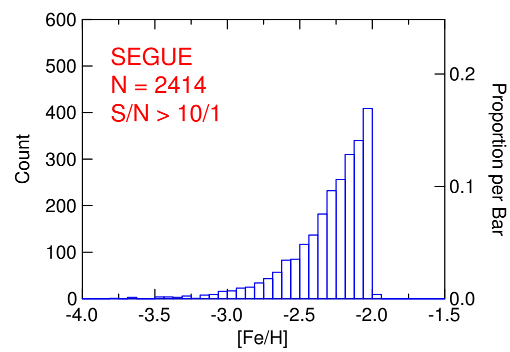

FIGURE 2. The MDF for VMP stars with 4500 K $< T_{\rm eff} <$ 7000 K observed during the course of the first year of SEGUE. These stars include objects specifically targeted to be likely VMP stars, as well as calibration stars.

THE DICHOTOMY OF THE GALACTIC HALO

The region of the Milky Way halo, beyond the thin- and thick-disk systems, has long been thought of as a single entity, comprising old stars and globular clusters that represent the earliest populations of objects to have formed in our Galaxy. Although many previous studies have speculated that the halo may in fact be partitioned into inner and outer components, possibly with different kinematics and spatial distributions, these studies have been limited by the generally small numbers of stars or globular clusters upon which this split could be made. Hence, it has always remained a suspicion, not a certainty. Until now. Based on medium-resolution spectroscopy for an initial sample of 20,366 SDSS calibration stars located within roughly 20 kpc of the Sun, Carollo et al. [5] have shown that the halo is clearly divisible into two broadly overlapping structural components. These are: (1) the in-

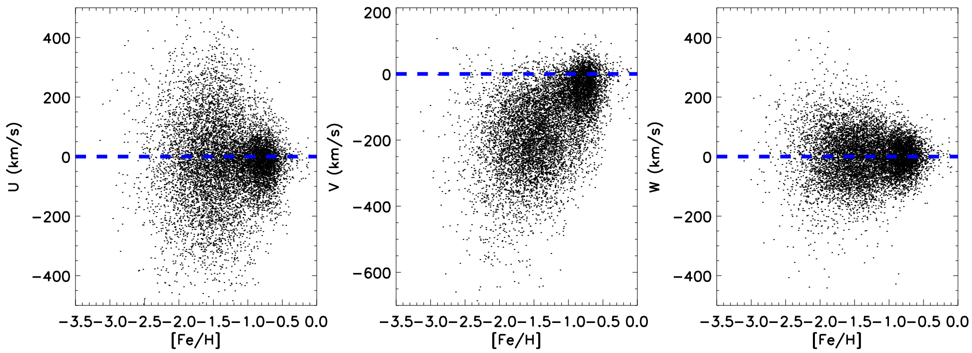

FIGURE 3. The components of space motion for the local sample of stars in Carollo et al., shown as a function of [Fe/H]. The dashed lines indicate the location of the Local Standard of Rest (LSR). As can be seen in the middle panel, the thick-disk and metal-weak thick disk population exhibits a small lag with respect to the LSR. Note also, in this panel, the large numbers of VMP stars with large retrograde motions ($V < -220$ km/s) with respect to the center of the Galaxy.

ner halo, which is dominated by stars on highly eccentric orbits and exhibits a peak metallicity [Fe/H] $= -1.6$, as well as a flattened density distribution with a modest net prograde rotation, and (2) the outer halo, which includes stars that possess a wide range of orbital eccentricities (including many on low eccentricity orbits), exhibits a peak metallicity [Fe/H] $= -2.2$, and a spherical density distribution with a highly statistically significant net retrograde rotation (between $V_\phi = -50$ and -80 km/s, depending on which subset of the data is considered).

The kinematic analysis of the Carollo et al. data set is carried out for the subset of over 11,000 stars located within 4 kpc of the Sun, where one can take advantage of the existence of reasonably accurate proper motions obtained from a re-calibration of the USNO-B catalog, as described by Munn et al. [8]. Typical errors in the derived proper motions are on the order of 2.5 to 3.5 mas/year, which is more than adequate for this exercise. Figure 3 shows the distribution of derived *UVW* components of the space motions for these stars as a function of [Fe/H], as determined by the SSPP. The impact of the size of this sample can be appreciated by comparing with similar diagrams in the article by Frebel et al. in this volume.

As is clear from inspection of Figure 3, one can clearly make out the presence of the concentrations of stars with relatively low space motions and moderately high metallicities, which we associate with membership in the thick-disk and metal-weak thick-disk populations. The very large velocity dispersions at lower metallicity are of course associated with the halo population(s) (which do not clearly separate from one another in such diagrams).

Stars in the disk population(s) can be effectively eliminated by considering only those stars on retrograde orbits. Furthermore, as one takes subsets of the stars that achieve maximum distances above the plane in the course of their orbits about the center of the Galaxy (Z_{max}) of 5 kpc or more, one can address whether or not they exhibit properties consistent with that expected from a single, or a more complex, halo population. Figure 4 shows the distribution of [Fe/H] for stars with varying levels of increasingly retrograde orbits, and with different cuts on Z_{max}. As is clear from inspection of this Figure, as one sweeps to more retrograde orbits, and to greater Z_{max}, the nature of the MDF changes over to favor stars at lower [Fe/H], and exhibits fewer stars with higher [Fe/H]. This is due to the change in the relative dominance of the outer-halo population over the inner-halo population at low metallicity and at distances greater than roughly 15-20 kpc from the Galactic center. This dichotomy may have a profound influence on searches for the most metal-poor stars in the Galaxy in the future, as described below.

FUTURE SEARCHES FOR THE MOST METAL-POOR STARS

There are two primary techniques that have been exploited to date for the identification of low-metallicity stars in the Galaxy. The first used selection of likely halo members based on observations of stars in the local volume of the Galaxy with relatively high proper motions, e.g., Ryan and Norris [9], or Carney et al. [10]. The second was based on the identification of stars from *in – situ* surveys (such as the HK survey and the HES) that sought to find halo members based on low-resolution objective-prism spectroscopy to a limiting magnitude between $B \sim 15.5$ (HK survey) and $B \sim 17.5$ (HES). The SDSS/SEGUE efforts are color-selected *in – situ* surveys, but many of the VMP stars identified to date are

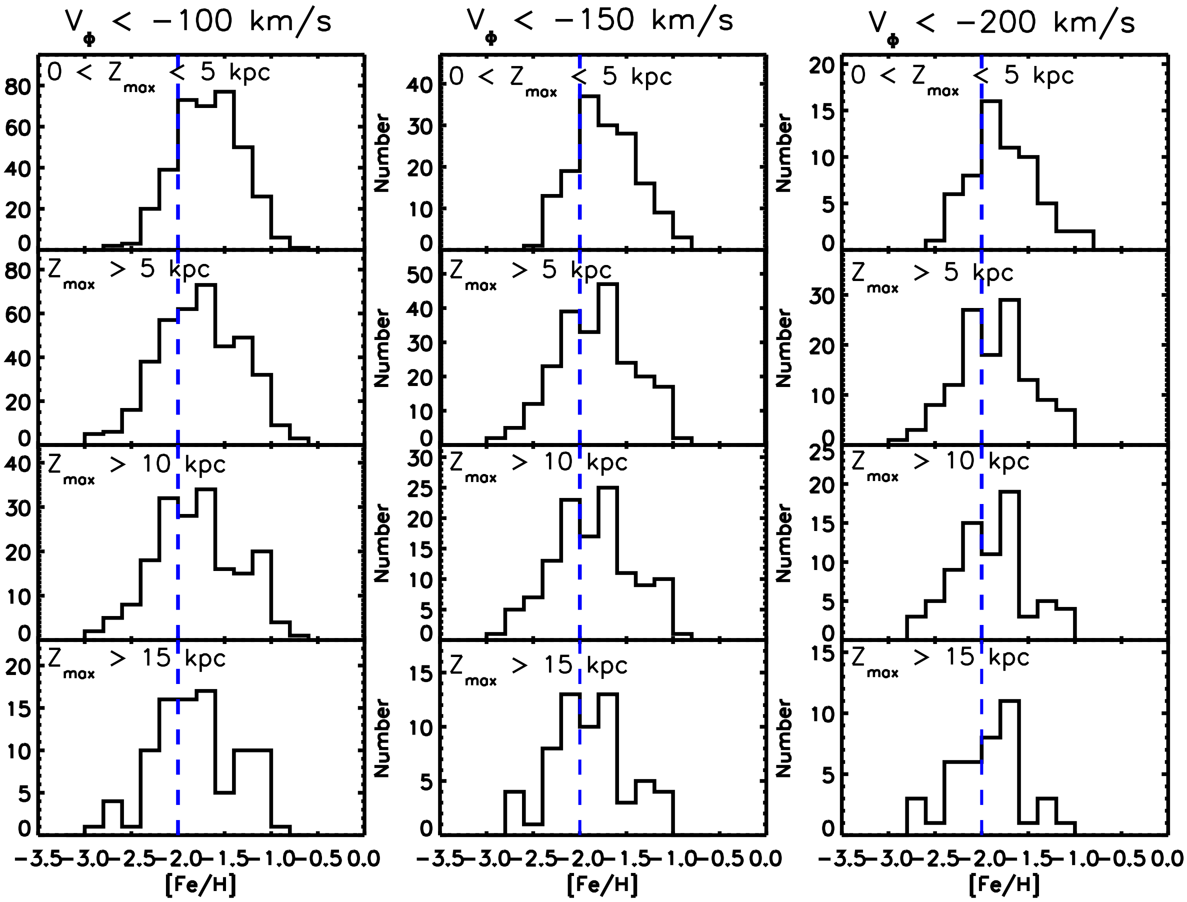

FIGURE 4. Plots of the MDFs for stars on highly retrograde orbits with respect to the Galactic center. The left hand column corresponds to stars with $V_\phi < -100$ km/s, while the middle and right-hand columns correspond to stars with more extreme retrograde motions, $V_\phi < -150$ km/s and $V_\phi < -200$ km/s, respectively. From top to bottom in each column, the panels show the MDFs for stars with increasing cuts on Z_{max}. The vertical lines at [Fe/H]$= -2.0$ are shown for reference. Note that the nature of the MDFs changes within each column, gradually favoring stars with [Fe/H] < -2.0 at higher Z_{max}. This change is even more evident (even though the total numbers of stars are fewer) for the most extremely retrograde columns. All of the cuts on individual panels with $Z_{max} > 5$ kpc are highly inconsistent, according to a K-S test, with being drawn from the same parent MDF as that of the low Z_{max} cuts shown in the upper panels.

still relatively local.

The interpretations of (in particular) the kinematics of stars selected by these two techniques has been the subject of much debate in the literature over the years. Now we understand why. Stars selected on the basis of high proper motions favor the identification of members of the outer-halo population, while the apparent-magnitude-limited prism (and color-selected) techniques favor stars from the inner-halo population. We presently estimate that no more than 20% of halo stars within 4 kpc from the sun are members of the outer-halo population, but this number has to be confirmed from more detailed modeling. The dominance of the inner halo continues to at least 10-15 kpc from the Sun; beyond that the outer-halo population begins to take over. Although there certainly exist EMP stars that are members of this inner-halo population, they are completely swamped by the huge numbers of stars near the peak of the inner-halo MDF around [Fe/H] $= -1.6$. It is surely no accident that the three UMP (which includes two HMP) stars known at present all are either located at distances greater than 10 kpc from the Sun, or, in the case of HE 1327-2326 (see Frebel et al. [8], and also Frebel et al., this volume), exhibit kinematics that place them firmly in the outer halo.

The clear recognition that outer-halo stars are drawn from a population with a lower peak in its MDF ([Fe/H] $= -2.2$) than that of the inner-halo stars ([Fe/H]$= -1.6$), and the smaller number of stars with [Fe/H] > -2.0 that appear among the outer-halo object,s suggests that one might seek to exploit these facts in future searches for the most metal-deficient stars. One could, for example, look to survey fainter stars, in particular distant giants, in order to reach stars well outside the region where the inner-halo dominates. Alternatively, one could make use of proper-motion surveys (now and in the future) to identify stars in the local volume with large components of their motions in the retrograde direction (or very high U or W motions), since this appears to strongly favor outer-halo membership. In this manner one might hope to efficiently identify sufficiently bright UMP and HMP stars that can be studied at high resolution with current generation 8m-10m class telescopes, and perhaps one day identify the long sought Mega Metal-Poor (MMP, with [Fe/H] < -6.0, according to [3]) stars.

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